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**MODELING AND ANALYSIS OF RENEWABLE ENERGY
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IN THE UK ELECTRICITY MARKET**

By

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Modeling and Analysis of Renewable Energy Obligations and Technology Bandings in the UK Electricity Market

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Abstract

In the UK electricity market generators are obliged to produce a certain amount of their electricity with renewable energy resources in accordance with the Renewable Obligation Order. This obligation comes with an (indirect) subsidy rewarding firms with tradable green certificates for their renewable energy production. Until 2009 every unit production of renewable energy was rewarded with the same amount of certificates. Since 2009 a banding has been added to the Renewable Order, meaning that different technologies are rewarded with a different number of certificates. The obligation then shifted from one on production to one on certificates. This paper discusses and analyzes these two different renewable obligation policies in a mathematical framework. The policies are modeled into a two-stage electricity market investment model in which firms invest at the first stage and produce at the second stage. Since banding may result in an outcome where the original obligation target is not satisfied, hence potentially resulting in more pollution, we present an alternative banding policy. We provide revenue adequate pricing schemes for the three obligation policies in order to guarantee that the regulator can cover the payments to firms owning certificates with the mark-ups paid by consumers. Then we move to a stochastic framework where the two main sources of uncertainty are the availability of renewable generation output and the stochastic nature of electricity demand. The stochastic framework is used to carry out a simulation study via sampling on a small network representing the UK market. We analyze the effects of the three obligation policies; a key finding is that, indeed, the UK banding policy cannot guarantee that the original obligation target is met. Our alternative provides a way to make sure that the target is met while supporting less established technologies, but it comes with a significantly higher consumer price. Furthermore, we observe a concerning side effect of banding policies, as a cost reduction in a technology with a high banding (namely offshore wind) leads to more CO₂ emissions under the UK banding policy and to higher consumer prices under the alternative banding policy.

Keywords: investment modeling in electricity markets, energy policy, renewable energy obligations,

green certificates, technology bandings, perfect competition equilibrium

JEL code: C61, C63, H23, Q58

1 Introduction

In decentralized electricity markets, firms are mainly focussed on maximizing their profits while competing with other firms. Investments in cheap and often polluting technologies tend to serve these goals well. This is in conflict with the goals set by governments as they aim at reducing pollution and want therefore to create incentives to make investments in cleaner technologies more attractive. Charging firms for their carbon dioxide (CO_2) emissions through either taxation or a cap-and-trade system in which firms need to buy emission permits, are two possible actions regulators can implement to make production with polluting technologies more expensive and therefore financially less attractive. Instead of charging firms for their emissions, governments may also hand out subsidies to firms for producing with clean technologies. That way investments in renewable technologies, which usually come with very high investment costs, become profitable. One can make a distinction between direct subsidies (usually in the form of Feed-in Tariffs) and indirect subsidies. In this paper we discuss the latter in more detail.

An indirect subsidy is usually given in the form of a renewable obligation. In several US states and in European countries like Belgium, Poland, Romania, Sweden, Italy, and UK, a renewable obligation is in effect.¹ The renewable obligation is a target on the proportion of electricity that should come from renewable resources and is set by the regulator on one group of operators in the market. Usually the obligation is imposed on consumption, through electricity sellers. In Italy however, the obligation is on the generators. So-called green certificates are used to show compliance to the target, and typically one such certificate represents 1 MWh of renewable electricity production. At the end of each obligation period, often a year, each seller or producer should submit a certain number of certificates to the regulator. When not satisfying the target, typically a buy-out fine has to be paid. The latter comes with an opportunity cost that puts a value on each certificate, which forms the price a seller is willing to pay to a renewable generator. The reward that generators receive adds to the short-term profits in a way that high long-term investment costs can be covered. Certificates can also be traded on a secondary market and as a consequence the renewable obligation does not oblige individual generators to produce a certain part of their electricity generation with renewable resources.

The UK and Italy form an exception to the system where one certificate represents 1 MWh of renewable electricity. In these countries certificates are banded according to technology, meaning that for different (renewable) technologies a different number of certificates is handed out per MWh of production. These so-called banding systems in the UK and Italy can help in encouraging investments in less developed technologies as to make them more competitive in the long run. This way it can overcome one of

¹For overviews of different support mechanisms across Europe, see Fouquet and Johansson (2008) and Koster et al. (2011).

the shortcomings of the regular renewable obligation which is known to single out the most developed technologies, namely onshore wind power and to a lesser extent landfill gas (see Meyer (2003), Wood and Dow (2011), and Verbruggen and Lauber (2012)). Although these technologies may be financially attractive, due to all kind of geographical constraints and opposition against onshore wind farms it is unlikely that the renewable obligation target can be met in the long run without investments in other renewable technologies like offshore wind, as emphasized by Toke (2011) and Wood and Dow (2011).

In this paper we investigate the effects of imposing a renewable obligation and introducing tradable green certificates. In particular, we focus on the (original) obligation system in the UK and take a closer look at their banding system in a mathematical and analytical framework. In order to analyze the system we extend the two stage investment model as introduced in Gürkan et al. (2012) by incorporating renewable obligations. In the mathematical model, investments are considered long-term decisions (for example yearly) which take place at the first stage. Production, transmission, and market clearing are short-term decisions (for example hourly or daily) that take place in the spot market, referred to as the second stage, which can be repeated several times. We assume perfect competition at both stages meaning that firms are price takers.

In order to make our model a good representation of reality and to keep results analytically tractable, we will make two simplifying assumptions with respect to the UK system. First of all, as mentioned earlier, in the UK the renewable obligation is imposed on total electricity sales. We assume though, that the firms producing power are selling their power directly to consumers, meaning that the obligation will be on electricity production. The second simplifying assumption concerns the trading of certificates. Recall that in the original obligation system each MWh of renewable energy production is rewarded with one renewable certificate. At the end of each period (typically a year) generators should submit a certain number of certificates proportional to the total production to show the obligation is met. In reality, the certificates can be traded daily on a secondary market and will have a certain value determined by the short term demand for certificates. Trading would be done on a daily basis and result in day to day variations in the value of a certificate. We overlook the micro details of the secondary trading market and therefore ignore the daily trading possibilities. Instead, we consider the average certificate value that holds over the year, which is directly related to the yearly obligation target. This average value is the reward the regulator pays firms per certificate. At the same time the consumer price is regulated in the form of a mark-up, as to cover the certificate payments.

After modeling the original renewable obligation into a mathematical framework, we take a closer look at the banding system that was introduced in the UK in 2009.² Under the banding policy, production with different renewable technologies is rewarded with a different number of certificates. As a consequence, some model adjustments need to be done; that is, we replace the obligation on production by one on certificates, and modify the pricing scheme defining the prices paid for production with non-renewable

²For a description of the UK (banding) system, see Constable and Barfoot (2008) and Clark (2008).

and renewable production and the consumer price. We analyze the consequences of the new policy and argue that the system can be effective in giving incentives to invest in less established technologies, but as an undesirable side effect may result in a more polluting mixture of technologies.

As a potential remedy for this negative side effect, we propose an alternative banding policy. In this alternative, production with different renewable technologies will be rewarded with a different amount of certificates in the same way as in the UK banding system. However, the obligation will be on renewable production rather than on certificates, similar to how it is done in the Italian banding system.³ Different from the Italian banding system, in which the regulator buys excess certificates, we make a modification to the reward per certificate in order to guarantee that rewards paid to firms are covered by mark ups paid by consumers, that is, to guarantee revenue adequacy for the regulator.

We then analyze the original obligation system, the UK banding system, and our proposed alternative in a numerical study where we assume uncertain demand and uncertain generation output of renewable resources. We focus on a small network with two non-renewable technologies (coal and combined cycle gas turbine (CCGT)) and three renewable technologies (onshore wind (ONW), offshore wind (OFFW), and landfill gas (LFG)) and obtain investment quantities, prices, and CO₂ emissions in all three systems. A key observation in all three systems is that the higher the obligation target, the more coal is replaced not only by renewable technologies, but also by CCGT which acts as a peak technology in case of high demand and/or low wind output. That way CO₂ emissions are curbed both by the increased renewable capacity and by the replacement of coal by the cleaner CCGT. Introducing the UK banding system has the effect of giving incentives for investments in OFFW, which were not present in the original system. However, bandings fail to create the right incentives when the obligation target is set too low. In that case the UK banding system may result in a cleaner mixture (but without OFFW) and overshoot the original target on production. On the other hand, when there are incentives to invest in OFFW we observe that for high obligation targets on certificates, the original target on production will not be satisfied. Hence, the UK banding system may lead to a more polluting technology mixture. Furthermore we observe that consumer prices in the UK banding system are not affected by having the more expensive OFFW in the mixture. Comparing the UK system to our alternative, we observe that the alternative needs higher obligation targets in order to create incentives for OFFW investments. When the obligation target is high enough for OFFW to be in the optimal mixture, we observe that consumer prices increase and exceed those obtained in the other systems.

Finally we analyze the effect of a decrease in the investment cost of OFFW. We find that investments are very sensitive to such a cost reduction and that under both banding policies there will be more OFFW in the system. Interestingly, although the investment quantities change, consumer prices in the UK banding system and CO₂ emissions in the alternative banding system remain unchanged. On the other hand, we observe a significant increase in consumer prices in the alternative system and considerably

³For a description of the Italian system, see Giovannetti (2009).

increased levels of CO₂ emissions in the UK banding system.

To summarize, the key findings in this paper are: First, the UK banding system may result in higher levels of CO₂ emissions compared to the original obligation system when OFFW is in the technology mixture; the alternative banding system proposes a possible solution for this undesirable side effect, albeit with relatively higher and less stable consumer prices. Second, cost reductions in a technology with high bandings (that is, OFFW), lead to increased levels of CO₂ emissions in the UK banding system and increased consumer prices in the alternative system. These are obviously negative side effects of banding systems, implying that as costs reduce, financial support and hence bandings should be reduced accordingly.

This paper is organized as follows. We introduce the basic electricity market investment model in Section 2 and expand this model to include the renewable obligation in Section 3. In Section 4 we introduce the concept of bandings. We explain the details of the UK banding system and propose an alternative system. In Section 5 we introduce uncertainty into the models. Both the generation output of renewable resources and electricity demand will be uncertain. The numerical study is carried out in Section 6. Section 7 concludes.

2 The Electricity Market Investment Model

In this section we introduce the electricity market investment model. Given is an electricity grid with supply nodes at which firms owning generation plants produce electricity using their technologies that are renewable or non-renewable, and demand nodes at which consumers with, by assumption, inelastic demand are located. Supply and demand nodes are connected by means of transmission lines with a given capacity, forming a network. Typically, when power is transmitted from one node to another through a transmission line, flows in the entire network are affected; furthermore, electricity cannot be stored. Firms at supply nodes make decisions in two stages. At the first stage all firms simultaneously maximize their profits while determining their optimal production capacity. Their profits are dependent on the equilibrium outcome at the second stage, which in return is dependent on the investment decisions of all firms at the first stage. The equilibrium at the second stage is between firms maximizing their profits while producing electricity given their production capacity in the first stage, a transmission system operator (TSO) owning the transmission grid, who is maximizing its own profits and taking care of the flows between supply and demand nodes, and subject to two types of market clearing conditions, an imposed price cap when there is unsatisfied demand, and a condition guaranteeing that demand is satisfied in all nodes. We assume perfect competition, and hence at both stages firms are not aware of the fact that they can influence prices. Since at the market equilibrium investment decisions of firms (indirectly) depend on decisions of other firms, we have a two stage game between the firms. When the first stage is solved to optimality and the second stage is at equilibrium, for none of the entities it is

profitable to deviate and thus a perfectly competitive equilibrium is obtained.

A suitable mathematical framework for the two-stage game is presented in Gürkan et al. (2012). They model the electricity market in a two-stage setting and show that under perfect competition the resulting two-stage game can be written as a single optimization problem when everything is deterministic, or as a standard two stage stochastic program in case of (demand) uncertainty at the second stage. In Gürkan et al. (2013) the same model is used for analyzing the consequences of imposing a taxation per unit emission or a cap-and-trade system. The latter means that firms have to buy permits on a secondary market in order to emit CO₂ and thus pay for their emissions. Instead of charging firms for their emissions, we will analyze the effects of imposing an indirect subsidy in the form of a renewable obligation, which will be the subject of Section 3. Before imposing the obligation, we provide an overview of the electricity market investment model as formulated in Gürkan et al. (2012) and Gürkan et al. (2013).

We make two adjustments to those models. First of all, for simplicity we assume that each firm has its own technology and is operational at all supply nodes (but not necessarily producing) for notational convenience. Second, we explicitly distinguish between a set of non-renewable technologies and a set of renewable technologies. The sets, parameters, and variables are given below.

Sets:

- N : the set of demand nodes
- I : the set of supply nodes
- K^N : the set of non-renewable technologies
- K^R : the set of renewable technologies
- K : the set of all technologies ($K := K^N \cup K^R$)
- L : the set of electricity transmission lines connecting nodes in the network.

Parameters:

- c_{ik} : unit production cost at supply node $i \in I$ for technology $k \in K$
- κ_{ik} : unit investment cost at supply node $i \in I$ for technology $k \in K$
- d_n : demand at demand node $n \in N$
- M_k^R : ceiling on investments in renewable technology $k \in K^R$
- $PTDF_{l,j}$: power transmitted through line $l \in L$ due to one unit of power injection into node $j \in N \cup I$
- h_l : capacity limit of line $l \in L$
- $VOLL$: value of unserved energy or lost load.

Variables:

- x_{ik} : generation capacity investment in technology $k \in K$ at supply node $i \in I$
- y_{ik} : quantity of power generated at supply node $i \in I$
by using technology $k \in K$
- f_j : net power flow dispatched by the TSO to node $j \in N \cup I$
- δ_j : unserved demand at node $j \in N \cup I$
- p_j^c : electricity price at node $j \in N \cup I$
- p_{ik}^N : price non-renewable technology $k \in K^N$ at supply node $i \in I$ gets per unit sold
- p_{ik}^R : price renewable technology $k \in K^R$ at supply node $i \in I$ gets per unit sold.

In the remainder of the paper, variables may get superscripts N and R depending on their corresponding technology in K^N and K^R , respectively. In addition, for $k \in K$ we define $x_k = (x_{ik})_{i \in I}$ and $y_k = (y_{ik})_{i \in I}$, the vectors containing investments and production, respectively, of technology $k \in K$ in all supply nodes.

We next formulate the first and second stage problems. At the first stage each firm $k \in K$ determines its optimal investment quantities x_k in all supply nodes, in order to maximize the optimal second stage profit minus the investment cost. The optimal second stage profit of technology $k \in K$ at supply node $i \in I$ is the price p_{ik} minus production cost c_{ik} , times the optimal second stage production y_{ik} as a function of investments x_k . Unit investment costs for technology $k \in K$ in supply node $i \in I$ are κ_{ik} . The first stage objective function for a non-renewable generator $k \in K^N$ looks as follows:

$$\max_{x_k^N \geq 0} \sum_{i \in I} (p_{ik}^N - c_{ik}^N) y_{ik}^N(x_k^N) - \sum_{i \in I} \kappa_{ik}^N x_{ik}^N. \quad (1)$$

$y_{ik}^N(x_k^N)$ is the optimal production quantity of technology k at supply node $i \in I$ at the second stage. Since firms are assumed to be price takers, for $i \in I$, p_{ik}^N is taken as a parameter. p_{ik}^N is typically equal to the consumer price in node i , p_i^c , but depending on the pricing scheme p_{ik}^N may be altered when for example an additional fee for a certificate or permit has to be paid. For a renewable generator $k \in K^R$ the first stage problem looks similar, namely:

$$\max_{x_k^R \geq 0} \sum_{i \in I} (p_{ik}^R - c_{ik}^R) y_{ik}^R(x_k^R) - \sum_{i \in I} \kappa_{ik}^R x_{ik}^R. \quad (2)$$

Again, for $i \in I$, $y_{ik}^R(x_k^R)$ is the optimal production quantity of technology k at supply node i at the second stage and p_{ik}^R is taken as a parameter. Again, typically p_{ik}^R is equal to p_i^c , but depending on the pricing scheme it may be altered. As we will see in the next section, introducing a renewable obligation may result in a difference between p^N and p^R . In addition, there can be a ceiling on capacity investments due to for example regulation or physical limitations. This is typical for some renewable technologies like

landfill gas. Hence, we add the following constraint that should be satisfied for technology $k \in K^R$:

$$\sum_{i \in I} x_{ik}^R \leq M_k^R \quad (\zeta_k^R), \quad (3)$$

where ζ_k^R is the nonnegative dual price associated with the ceiling. We provide an interpretation of this dual price at the end of this section.

At the second stage each firm determines its optimal production quantities while maximizing its second stage profit, subject to the capacity constraint. The investment quantities from the first stage are given and treated as parameters. For each renewable technology $k \in K^R$ in supply node $i \in I$ we define $F_{ik}(\cdot)$ as some differentiable possibly nonlinear (stochastic) nondecreasing function of the investment x_{ik}^R , with $F_{ik}(0) = 0$, denoting the available capacity. For example, $F_{ik}(\cdot)$ can be $F_{ik}(x) = \sqrt{x}$ in which case the available capacity is deterministic and known in advance, or one can have $F_{ik}(x, \omega) = \theta_{ik}(\omega)x$, where $\theta_{ik}(\omega) \sim \text{uniform}(\frac{1}{2}, 1)$. Parameter θ_{ik} then represents the fraction of capacity in technology k at node i that is available. In general $F_{ik}(\cdot)$ should reflect the fact that for most renewable resources like wind power, not all installed capacity is available for generation at all times. We discuss this in more detail in Section 5. The second stage problem for a non-renewable generator $k \in K^N$ is

$$\begin{aligned} \Pi_k^N(x_k^N) := \max_{y_k^N} \quad & \sum_{i \in I} (p_{ik}^N - c_{ik}^N) y_{ik}^N \\ \text{s.t.} \quad & y_{ik}^N \leq x_{ik}^N \quad (\beta_{ik}^N) \quad \forall i \in I \\ & y_{ik}^N \geq 0 \quad \forall i \in I. \end{aligned} \quad (4)$$

For a renewable generator $k \in K^R$ we have:

$$\begin{aligned} \Pi_k^R(x_k^R) := \max_{y_k^R} \quad & \sum_{i \in I} (p_{ik}^R - c_{ik}^R) y_{ik}^R \\ \text{s.t.} \quad & y_{ik}^R \leq F_{ik}(x_{ik}^R) \quad (\beta_{ik}^R) \quad \forall i \in I \\ & y_{ik}^R \geq 0 \quad \forall i \in I. \end{aligned} \quad (5)$$

The β s are the dual variables associated with the capacity constraints and represent the scarcity rents.

The produced electricity is transmitted from the supply nodes to the demand nodes by the Transmission System Operator (TSO). The TSO determines the optimal net flow f_j into node $j \in N \cup I$. Having $f_j < 0$ means there is a flow out of node j (which usually holds for the supply nodes). Power is transmitted through transmission lines $l \in L$. Each line in L runs from one node to another node. Each flow affects the capacities on all lines in the network either positively or negatively in accordance with Kirchhoff's Law; see for example Chao et al. (2000). Kirchhoff's Law is taken into account via the commonly used power transmission distribution factors (PTDF), which are given for a given network. For the network flows to be feasible, it must hold that the net load on line $l \in L$ must lie between the

network capacities $-h_l$ and h_l . TSO's problem is to maximize the total value of the flows and can be written as:

$$\begin{aligned}
& \max_f \quad \sum_{j \in N \cup I} p_j^c f_j \\
& s.t. \quad \sum_{j \in N \cup I} f_j = 0 \quad (\rho) \\
& \quad h_l - \sum_{j \in N \cup I} PTDF_{l,j} f_j \geq 0 \quad (\lambda_l^+) \quad \forall l \in L \\
& \quad h_l + \sum_{j \in N \cup I} PTDF_{l,j} f_j \geq 0 \quad (\lambda_l^-) \quad \forall l \in L.
\end{aligned} \tag{6}$$

The first constraint is the flow balance constraint with dual price ρ , and the last two constraints take care of the transmission capacity on the lines $l \in L$ and have dual prices λ_l^+ and λ_l^- , respectively.

Finally, two market clearing conditions should hold at equilibrium. First, in each supply node $i \in I$, where the demand is defined as $d_i = 0$, the flow out of this node can be at most equal to the total production in that node. In each demand node $n \in N$, where the supply is defined as $y_{nk}^N = 0 \quad \forall k \in K^N$ and $y_{nk}^R = 0 \quad \forall k \in K^R$, the flow into this node should be at least equal to the demand d_n (unless there is unsatisfied demand as we explain below). Perpendicular to those conditions, the market price p_j^c in each node $j \in N \cup I$ is determined. Second, there may be unsatisfied demand at node $j \in N \cup I$ which we denote by δ_j . Whenever the unsatisfied demand is positive, the market price in node j should be set to $VOLL$, the Value Of Lost Load, or to a high price-cap. In other words, $VOLL$ can essentially serve as a price-cap and is in general taken as a high number, compared to regular electricity prices. The above relations are described by the following conditions:

$$\begin{aligned}
0 \leq \sum_{k \in K^N} y_{jk}^N + \sum_{k \in K^R} y_{jk}^R + \delta_j + f_j - d_j & \perp p_j^c \geq 0 \quad \forall j \in N \cup I \\
0 \leq VOLL - p_j^c & \perp \delta_j \geq 0 \quad \forall j \in N \cup I.
\end{aligned} \tag{7}$$

The second stage problem now consists of the firms' problems (4) and (5), the TSO's problem (6), and the two types of market clearing conditions (7). After specifying the prices p^N and p^R in relation to p^c in each node, the entire second stage can be written as a single optimization problem, the Optimal Power Flow (OPF) problem, as shown in Gürkan et al. (2012). Solving the OPF problem results in an equilibrium at the second stage. This will be further discussed in the next section.

Given an equilibrium at the second stage, firms determine their first stage investment quantities based on the information from the second stage. In order to establish the connection between the two stages we write the KKT-optimality conditions that need to be solved for first stage optimality. The KKT-optimality conditions of the first stage problem given by (1) are:

$$0 \leq x_{ik}^N \quad \perp \quad -\beta_{ik}^N + \kappa_{ik}^N \geq 0 \quad \forall i \in I, k \in K^N \tag{8}$$

These conditions follow from writing the Lagrangian function of (1) and taking derivatives with respect

to x_{ik}^N , $i \in I$, $k \in K^N$. A detailed derivation of these first stage conditions can be found in Gürkan et al. (2012). For every $i \in I$, $k \in K^N$, at least one of the two sides in (8) should hold with equality, and hence there can only be a positive investment in technology $k \in K^N$ in supply node $i \in I$ if the corresponding scarcity rent that is taken from the second stage equilibrium, β_{ik}^N , covers the investment cost κ_{ik}^N . β_{ik}^N can now be interpreted as the value of an additional unit investment in technology $k \in K^N$ in supply node $i \in I$.

The KKT-optimality conditions of the first stage problem given by (2) and (3) are:

$$\begin{aligned} 0 \leq x_{ik}^R & \quad \perp \quad -F'_{ik}(x_{ik}^R)\beta_{ik}^R + \kappa_{ik}^R + \zeta_k^R \geq 0 & \quad \forall i \in I, k \in K^R \\ 0 \leq \zeta_k^R & \quad \perp \quad M_k^R - \sum_{i \in I} x_{ik}^R \geq 0 & \quad \forall k \in K^R. \end{aligned} \quad (9)$$

These conditions follow from writing the Lagrangian function of (2) subject to (3), and taking derivatives with respect to x_{ik}^R , $i \in I$, $k \in K^R$ and ζ_k^R , $k \in K^R$. The first condition means that at least one of the two sides should hold with equality and hence there can only be a positive investment in technology $k \in K^R$ in supply node $i \in I$ if $F'_{ik}(x_{ik}^R)\beta_{ik}^R$ covers the sum of the investment cost κ_{ik}^R and the dual price associated with the ceiling ζ_k^R . β_{ik}^R is the scarcity rent corresponding to a unit production, and $F'_{ik}(x_{ik}^R)$ is the change in production corresponding to a unit change in investment. Hence, $F'_{ik}(x_{ik}^R)\beta_{ik}^R$ represents the scarcity rent of a unit investment. ζ_k^R can be seen as the additional scarcity rent that comes with the ceiling, M_k^R . When the ceiling becomes binding, another, more expensive technology will be used to satisfy demand. As a consequence prices and hence scarcity rents increase with the additional rent ζ_k^R . The second condition in (9) guarantees that ζ_k^R is zero whenever the ceiling is not binding.

Finally, we analyze the equilibrium to the two stage game (1)-(7). The following theorem summarizes its key properties.

Theorem 2.1. *Consider the two-stage optimization problem defined by (1)-(7). At the equilibrium, the following holds.*

For investment in non-renewable technology $k \in K^N$ in supply node $i \in I$ to be positive, it must hold that

- $p_{ik}^{*N} - c_{ik}^N = \kappa_{ik}^N$
- $\beta_{ik}^{*N} = \kappa_{ik}^N$
- $y_{ik}^{*N} = x_{ik}^{*N}$

For investment in renewable technology $k \in K^R$ in supply node $i \in I$ to be positive, it must hold that

- $F'_{ik}(x_{ik}^R)(p_{ik}^{*R} - c_{ik}^R) = \kappa_{ik}^R + \zeta_k^{*R}$
- $F'_{ik}(x_{ik}^R)\beta_{ik}^{*R} = \kappa_{ik}^R + \zeta_k^{*R}$
- $y_{ik}^{*R} = F_{ik}(x_{ik}^{*R})$

Proof: Suppose investment in non-renewable technology $k \in K^N$ in supply node $i \in I$ is positive, that is, $x_{ik}^{*N} > 0$. If $p_{ik}^{*N} - c_{ik}^N < \kappa_{ik}^N$, by $y_{ik}^{*N} \leq x_{ik}^{*N}$ firm k has a negative first stage profit in supply node i and is

better off with no investments. On the other hand, if $p_{ik}^{*N} - c_{ik}^N > \kappa_{ik}^N$, firm k 's investment goes to infinity and hence we have no equilibrium. Hence, $p_{ik}^{*N} - c_{ik}^N = \kappa_{ik}^N$. $\beta_{ik}^{*N} = \kappa_{ik}^N$ follows immediately from (8) and $x_{ik}^{*N} > 0$. $y_{ik}^{*N} = x_{ik}^{*N}$ must hold, since by complementary slackness in (5), $y_{ik}^{*N} < x_{ik}^{*N}$ implies $\beta_{ik}^{*N} = 0$ which contradicts our previous statement. The proof for renewable technology $k \in K^R$ is similar and is omitted. \square

Note that $F'_{ik}(x_{ik}^R)(p_{ik}^{*R} - c_{ik}^R) = \kappa_{ik}^R + \zeta_k^{*R}$ can be interpreted as follows. On the left hand side, $p_{ik}^{*R} - c_{ik}^R$ is the net marginal revenue of production, and taking the derivative of production with respect to investment gives us the net marginal revenue of investment. At the equilibrium, this net marginal revenue of investment should be equal to the right hand side, which is the net marginal cost of investment including the additional scarcity rent for investment in case (3) is binding.

In the absence of environmental regulation to encourage investments in renewable technologies, both the price for non-renewable technologies and for renewable technologies are typically set at the consumer price. Together with the results in Theorem 2.1, this implies the following. In each supply node $i \in I$ only a single technology, namely the one with the lowest sum of per unit production and investment cost, has a positive investment. The consumer price and hence the price for all technologies in node $i \in I$ will be set equal to this sum. In reality, whenever there is a non-renewable technology available in a node, none of the renewable technologies will have a positive investment because of its high investment cost. However, given that we can have different prices for both non-renewable and renewable technologies, we can incorporate some regulation that will set the price for renewable technologies higher as to create a financial incentive for investment in some $k \in K^R$ to be positive. We do this in the next section by introducing a renewable obligation that comes with a reward for producing with renewable technologies.

3 Introducing a Renewable Obligation and Tradable Green Certificates

We introduce a renewable obligation target in the electricity market investment model that was introduced in the previous section. An obligation target, denoted by ϕ , is set by the regulator. $\phi \in [0, 1]$ is the minimum proportion of total electricity production that should come from renewable resources. Let $Y^N = \sum_{i \in I} \sum_{k \in K^N} y_{ik}^N$ and $Y^R = \sum_{i \in I} \sum_{k \in K^R} y_{ik}^R$ be the total production using non-renewable and renewable plants, respectively. Given the obligation target it should hold that

$$\frac{Y^R}{Y^R + Y^N} \geq \phi. \quad (10)$$

Production with renewable resources is in general more expensive (when considering both investment and production cost) than production with non-renewable resources. The obligation (10) forces producers to replace non-renewable production with renewable production and thus comes with a certain additional cost. We let ν be the cost incurred with a unit increase of renewable production. More specifically, ν can be seen as the dual variable to (10) and represents the mark-up renewable generators should get in order to increase their production by one unit. These mark-ups are given to the firms through certificates. For each unit production, a renewable certificate is obtained and ν should thus be the value of such a certificate. Certificates can either be traded on a secondary market, or sold to the regulator to show compliance to the obligation. When trading is considered, ν would be the fair price for each certificate. When, like we assume, the regulator rewards firms for owning certificates, ν is the reward per certificate firms get paid at the end of each period, typically a year. ν is thus referred to as the certificate price (from the regulator's perspective) or reward (from the firm's perspective). Rewriting (10) with ν as its dual variable, leads to the following complementarity condition that should hold at equilibrium:

$$0 \leq \sum_{k \in K^R} (1 - \phi) Y_k^R - \sum_{k \in K^N} \phi Y_k^N \quad \perp \quad \nu \geq 0, \quad (11)$$

where $Y_k^R := \sum_{i \in I} y_{ik}^R$ for $k \in K^R$ and $Y_k^N := \sum_{i \in I} y_{ik}^N$ for $k \in K^N$. These aggregate variables per technology will be used in the remainder of the paper to simplify notation.

We next consider the effect of rewards on the nodal prices. The electricity price in each supply node is usually set by the technology that produces with the highest marginal production cost. Since the fuel cost and hence the unit production cost (as opposed to the unit investment cost) of renewable technologies will in general be very low, without loss of generality we can assume that the electricity price will be set by a non-renewable technology. We refer to this price as the base price in node $i \in I$ and denote it by p_i^N . When power is bought from a non-renewable generator $k \in K^N$, the price paid per unit thus equals $p_{ik}^N = p_i^N$. When a renewable generator $k \in K^R$ sells power, it sells both the power (at price p_i^N) to the consumer and the certificate (at price ν) to the regulator, and should therefore be paid $p_{ik}^R = p_i^N + \nu$.

In electricity markets consumers typically pay a fixed consumer price that is independent of the resource. If consumers would only pay the electricity price p_i^N in every node i , the rewards paid to the firms could not be covered. The regulator therefore regulates the consumer price and adds a mark-up on top of p_i^N . The mark-up is set in such a way that the additional income covers the rewards paid to firms for owning certificates (that is, to guarantee revenue adequacy). Since a part ϕ of the total production should come from renewable resources, given that the total production equals $Y (= Y^N + Y^R)$, the total renewable production should be ϕY . This is also the number of times a reward should be paid to the firms. Hence, the mark-ups for the consumer price should cover $\phi Y \nu$. Furthermore, we want the mark-up to be equal in each node i ; that is, although the electricity price can be different in each node due to the network structure, the certificate price and thus the mark-up are the result of putting a constraint on

the entire market and hence should not be different for different nodes. Assuming that all the produced power will be sold, it should hold that the mark-up Δp^c is the solution of $\Delta p^c Y = \phi Y \nu$, resulting in a consumer price equal to $p_i^c = p_i^N + \phi \nu$, $i \in I$. This is imposed in the following pricing scheme:

$$\begin{aligned} p_{ik}^N &= p_i^N & \forall i \in I, k \in K^N \\ p_{ik}^R &= p_i^N + \nu & \forall i \in I, k \in K^R \\ p_i^c &= p_i^N + \phi \nu & \forall i \in I. \end{aligned} \tag{12}$$

Given this pricing scheme, we can express both p_{ik}^N and p_{ik}^R in (4) and (5) in terms of p_i^c ; that is, $p_{ik}^N = p_i^c - \phi \nu$ for $k \in K^N$ and $p_{ik}^R = p_i^c + (1 - \phi) \nu$ for $k \in K^R$. We show that with this pricing scheme a solution for the entire second stage problem can be obtained by solving an Optimal Power Flow (OPF) problem. First, let us write the KKT conditions of the second stage problems (4), (5), (6), and the market clearing conditions (7) for given x :

$$\begin{aligned} 0 \leq \beta_{ik}^{*N} - p_i^{*c} + \phi \nu^* + c_{ik}^N &\perp y_{ik}^{*N} \geq 0 & \forall i \in I, k \in K^N \\ 0 \leq \beta_{ik}^{*R} - p_i^{*c} - (1 - \phi) \nu^* + c_{ik}^R &\perp y_{ik}^{*R} \geq 0 & \forall i \in I, k \in K^R \\ 0 \leq x_{ik}^N - y_{ik}^{*N} &\perp \beta_{ik}^{*N} \geq 0 & \forall i \in I, k \in K^N \\ 0 \leq F_{ik}(x_{ik}^R) - y_{ik}^{*R} &\perp \beta_{ik}^{*R} \geq 0 & \forall i \in I, k \in K^R \\ 0 \leq VOLL - p_j^{*c} &\perp \delta_j^* \geq 0 & \forall j \in N \cup I \\ 0 \leq \sum_{k \in K^N} y_{jk}^{*N} + \sum_{k \in K^R} y_{jk}^{*R} + \delta_j^* + f_j^* - d_j &\perp p_j^{*c} \geq 0 & \forall j \in N \cup I \\ 0 \leq \sum_{i \in I} \sum_{k \in K^R} (1 - \phi) y_{ik}^{*R} - \sum_{i \in I} \sum_{k \in K^N} \phi y_{ik}^{*N} &\perp \nu^* \geq 0 \\ 0 \leq h_l - \sum_{j \in N \cup I} PTDF_{l,j} f_j^* &\perp \lambda_l^{*+} \geq 0 & \forall l \in L \\ 0 \leq h_l + \sum_{j \in N \cup I} PTDF_{l,j} f_j^* &\perp \lambda_l^{*-} \geq 0 & \forall l \in L \\ p_j^{*c} - \rho^* + \sum_{l \in L} PTDF_{l,j} (\lambda_l^{*+} - \lambda_l^{*-}) = 0 & & \forall j \in N \cup I \\ \sum_{j \in N \cup I} f_j^* = 0. \end{aligned} \tag{13}$$

Now we can write the above system as a single optimization problem; that is, the OPF problem:

$$\begin{aligned}
Z(x) := \min_{y, \delta, f} \quad & \sum_{i \in I} \sum_{k \in K^N} c_{ik}^N y_{ik}^N + \sum_{i \in I} \sum_{k \in K^R} c_{ik}^R y_{ik}^R + VOLL \sum_{j \in N \cup I} \delta_j \\
s.t. \quad & y_{ik}^N \leq x_{ik}^N & (\beta_{ik}^N) & \forall i \in I, k \in K^N \\
& y_{ik}^R \leq F_{ik}(x_{ik}^R) & (\beta_{ik}^R) & \forall i \in I, k \in K^R \\
& \sum_{k \in K^N} y_{jk}^N + \sum_{k \in K^R} y_{jk}^R + \delta_j + f_j \geq d_j & (p_j^c) & \forall j \in N \cup I \\
& \sum_{i \in I} \sum_{k \in K^R} (1 - \phi) y_{ik}^R - \sum_{i \in I} \sum_{k \in K^N} \phi y_{ik}^N \geq 0 & (\nu) & \\
& \sum_{j \in N \cup I} f_j = 0 & (\rho) & \\
& \sum_{j \in N \cup I} PTDF_{l,j} f_j \leq h_l & (\lambda_l^+) & \forall l \in L \\
& \sum_{j \in N \cup I} PTDF_{l,j} f_j \geq -h_l & (\lambda_l^-) & \forall l \in L \\
& y_{ik}^N \geq 0 & & \forall i \in I, k \in K^N \\
& y_{ik}^R \geq 0 & & \forall i \in I, k \in K^R \\
& \delta_j \geq 0 & & \forall j \in N \cup I.
\end{aligned} \tag{14}$$

A solution (y^*, δ^*, f^*) of the OPF problem satisfies KKT-conditions (13) for some $\beta^*, p^{*c}, \nu^*, \rho^*, \lambda^{*+}, \lambda^{*-}$. More details on the derivation for the base case model can be found in Boucher and Smeers (2001) and Gürkan et al. (2012); ours is a straight forward extension. Solving the OPF problem gives a second stage equilibrium for given x . The entire investment problem can now be solved by finding an equilibrium to the second stage problem (14) together with the first stage optimality conditions consisting of (8) and (9).

In Theorem 2.1 we gave properties of x^*, y^*, p^* , and β^* at the equilibrium. Given the pricing scheme (12), we can now replace the prices and analyze the equilibrium in case of a renewable obligation. Recall that for a non-renewable technology $k \in K^N$ to have positive investments in supply node $i \in I$ it should hold that $p_{ik}^{*N} - c_{ik}^N = \kappa_{ik}^N$. Rewriting using (12) gives $p_i^{*c} = c_{ik}^N + \kappa_{ik}^N + \phi \nu^*$. Furthermore we have $\beta_{ik}^{*N} = \kappa_{ik}^N$ and $y_{ik}^{*N} = x_{ik}^{*N}$, $k \in K^N$, $i \in I$. Only one non-renewable technology will have a positive investment and will thus set the price for non-renewable technologies. For a renewable technology $k \in K^R$ to have positive investments in supply node $i \in I$, it must hold that $F'_{ik}(x_{ik}^R)(p_i^{*R} - c_{ik}^R) = \kappa_{ik}^R + \zeta_k^{*R}$; rewriting using our pricing scheme (12), we get

$$p_i^{*c} = c_{ik}^R + \frac{1}{F'_{ik}(x_{ik}^R)}(\kappa_{ik}^R + \zeta_k^{*R}) - (1 - \phi)\nu^*. \tag{15}$$

In addition, when investment is positive, we have $F'_{ik}(x_{ik}^R)\beta_{ik}^{*R} = \kappa_{ik}^R + \zeta_k^{*R}$, and $y_{ik}^{*R} = F_{ik}(x_{ik}^{*R})$. Due to the obligation, ν^* will now be set such that at least a fraction ϕ will be produced with renewable

technologies, and hence at least one renewable technology must have a positive investment. Depending on the caps on investment quantities M_k^R , $k \in K^R$, multiple renewable technologies can be in the equilibrium mixture. All capacity of the cheapest renewable technology (in terms of the sum of their production and investment cost), let's say $k^0 \in K^R$, would be used up first. If that is not sufficient to satisfy the obligation, k^0 would invest up to his maximum capacity and $\zeta_{k^0}^{*R}$ would become positive. The next cheapest renewable technology will be used and as such the consumer price in node i , p_i^{*c} , will increase. $\zeta_{k^0}^{*R}$ will be determined such that the equality in (15) for technology k^0 still holds and can thus be seen as the additional rent for investment in technology k^0 due to the ceiling.

Since only the cheapest firms invest at the equilibrium, the deterministic equilibrium can simply be based on all the parameters and is thus quite straightforward. In reality, broader mixtures of technologies are used, which is the result of daily uncertainties like demand and weather fluctuations. We therefore continue our analysis of the effects of the renewable obligation in Sections 5 and 6 where we deal with a stochastic version of the model and carry out a numerical study. Before doing so, we first extend the renewable obligation to the case in which different renewable technologies are eligible for a different number of certificates per unit production.

4 Introducing a Banding System

The previously introduced model was applicable to the UK system until the 1st of April 2009, when the Renewable Obligation Order 2009 became effective.⁴ In this regulatory document a banding system was added to the renewable obligation. In the old system, a unit production with a renewable technology was eligible for one renewable energy certificate and hence would receive the certificate price for each unit production. In the new system, renewable certificates are banded according to technology. This means that different renewable technologies are eligible for a different number of certificates. The main reason for introducing bandings is to encourage investments in less established technologies (by giving them more certificates per unit production). The original renewable obligation failed to give the right financial incentives as it tended to mainly benefit onshore wind power and landfill gas, as noted by Meyer (2003). As argued by Toke (2011) and Wood and Dow (2011), investments in these more established technologies are limited not by the lack of financial incentives, but mostly because of landscape protection, public opposition, and space. Therefore, investment in less developed technologies will be necessary in order to be able to achieve the ambitious renewable energy targets.

In the new system onshore wind is used as the reference for bandings. A unit production with onshore wind is rewarded with one certificate, less established technologies like offshore wind and geothermal are rewarded with 1.5 and 2 certificates, respectively, and more established technologies like sewage gas and landfill gas are rewarded with only 0.5 and 0.25 certificates, respectively. The regulator may change

⁴See <http://www.legislation.gov.uk/uksi/2009/785/contents/made?view=plain>.

these coefficients from time to time when a different support is desirable. This has recently been done for offshore wind, which now will get 2 certificates per unit production until 2014.

In this section we first incorporate the UK banding system into the existing model. We introduce a pricing scheme and analyze the advantages and drawbacks of the new system. Then we propose an alternative that is closer to the Italian banding system in order to overcome some of these drawbacks.

4.1 The UK Banding System

With the banding system as introduced in the UK, the obligation shifts from one on the renewable production to one that is expressed as the number of certificates that should be presented by the entire market at the end of each period. Hence, with the new system, obligation constraint (11) should be replaced by a condition of the following form:

$$0 \leq \sum_{k \in K^R} \alpha_k Y_k^R - R \quad \perp \quad \nu \geq 0, \quad (16)$$

where R is the number of certificates all firms together have to present, and α_k is the number of certificates firm $k \in K^R$ receives for producing one unit of electricity with renewable technology $k \in K^R$.

As explained in great detail in the Renewable Obligation Order 2009, in order to determine R , the UK regulator performs two calculations estimating the number of certificates that should or can potentially be issued. Whichever calculation gives the highest estimate will be set as the obligation target R . The first calculation, Calculation A, is based on a fixed target representing the number of certificates firms should produce per unit of electricity produced. This target is in fact the original obligation target ϕ that was used in system (11). The total number of certificates that should be issued based on this fixed target is simply ϕ times the expected total electricity production and will be defined as A .

In the second calculation, Calculation B, the number of certificates that is likely to be issued, given the existing renewable production capacity and the expected new built capacity, is estimated. In addition a headroom of 8% is added. The outcome is defined as B .

In practice this means that if $A > B$, it is expected that the existing and expected new built capacity will not be sufficient to reach the original obligation target ϕ that was used for Calculation A. Hence, the target is set at A to oblige firms to install additional renewable capacity. If $B > A$, it means that there is already sufficient existing plus expected new built capacity in the system. When this happens, the original target ϕ may be met quite easily and as a consequence the value of certificates may drop to zero, resulting in an unfavorable situation for the renewable generators. Setting the obligation target at B should avoid this. In order to provide even more security and to give extra incentives, an additional headroom of 8% is added to the originally computed expected number of certificates that is likely to be issued.

After the target $R = \max\{A, B\}$ is determined, the regulator obliges all firms to produce a certain

number of certificates per unit production. If $A > B$, each firm will need to submit ϕ certificates per unit production. If $B > A$ each firm will have to submit $\phi^B = \frac{\phi A}{B}$ certificates per unit production. Since we assume perfect competition and deal with certificates that can be traded on a secondary market, this obligation per firm can also be seen as one for the entire market. We let ϕ^{UK} be the target on certificates based on the calculations above (either ϕ or ϕ^B), which means that R , the total number of certificates that should be presented, equals ϕ^{UK} times the total production. Hence, replacing R in (16), the obligation can be written as

$$0 \leq \sum_{k \in K^R} (\alpha_k - \phi^{UK}) Y_k^R - \sum_{k \in K^N} \phi^{UK} Y_k^N \quad \perp \quad \nu \geq 0. \quad (17)$$

Since different technologies are rewarded with a different number of certificates, prices paid to the generators will depend on the technology used. Therefore we will have to adjust the pricing scheme (12) introduced under the original renewable obligation. Per unit production in any supply node $i \in I$, a renewable technology $k \in K^R$ is given α_k certificates. Since, when selling the electricity, firms also sell their certificates, renewable technology $k \in K^R$ is then paid the base price, p_i^N , plus α_k times the certificate price ν . In the corresponding pricing scheme we get that $p_{ik}^N = p_i^N$, $k \in K^N$, $i \in I$ and $p_{ik}^R = p_i^N + \alpha_k \nu$, $k \in K^R$, $i \in I$. With a consumer price similar to the one in (12), namely $p_i^c = p_i^N + \phi^{UK} \nu$, $i \in I$, it turns out that mark ups paid by consumers equal the rewards paid to firms for owning certificates. That is, renewable technologies are paid $\nu \sum_{k \in K^R} \alpha_k Y_k^R$, which by (17) equals $\nu \phi^{UK} Y$. It can easily be seen that $\nu \phi^{UK} Y$ is the total mark ups paid by consumers, and hence rewards paid to firms are covered. This means the pricing scheme is revenue adequate. Summarizing, the adjusted pricing scheme for the UK banding system becomes

$$\begin{aligned} p_{ik}^N &= p_i^N & \forall i \in I, k \in K^N \\ p_{ik}^R &= p_i^N + \alpha_k \nu & \forall i \in I, k \in K^R \\ p_i^c &= p_i^N + \phi^{UK} \nu & \forall i \in I. \end{aligned} \quad (18)$$

Note that ideally it would hold that, with the obligation on certificates, a fraction ϕ^{UK} of the total production comes from renewable resources like in the old obligation system. However, since there is no one-to-one relationship between renewable production and certificates anymore, this is not necessarily the case. In case a major part of the obligation is satisfied by a technology with a high banding coefficient, the actual renewable production may be (much) lower than the desired target on production and as a consequence the banding system could result in a more polluting mixture of technologies. In general, Calculation B may set the target on certificates a bit higher than the original obligation ϕ , but when there are technologies with a high banding coefficient, one may not guarantee that the original target on renewable production is met unless the target on certificates is increased accordingly.

We will come back on this issue in our numerical study. In the next section, we propose an alternative system that combines features of the original obligation and the UK banding system.

4.2 An Alternative Banding System

As the UK banding system does not necessarily guarantee that the obligation target on renewable production (11) is satisfied and may even result in a more polluting mixture, we propose an alternative banding system. Unlike in the UK banding system where the obligation shifted to one on certificates, the obligation will be imposed on production in the same way it was done in the original renewable obligation (that is, as in (11) as opposed to (17)). On the other hand, certificates will still be handed out based on the pre-specified banding coefficients. Since in this case we no longer have a one-to-one correspondence between a unit of renewable production and a certificate, and since the target is no longer on certificates like in the UK banding system, the dual price ν in (11) no longer represents the value of a certificate; it just represents the value of a unit production with a renewable resource. This will have a consequence for the reward per certificate and hence for the pricing scheme.

As we have seen, under the previously discussed obligation policies consumers pay a mark-up that covers the rewards the regulator pays to the firms for owning certificates; in other words, the proposed pricing schemes are revenue adequate for the regulator. We would like this revenue adequacy to hold in the alternative system as well. In the UK banding system, in the pricing scheme (18), the consumer price was set at $p_i^c = p_i^N + \phi\nu$. We adopt this price in our alternative system as this price does not depend on the α_k s and hence on the technologies used, which is typically the case in electricity markets. With this price the total income from mark-ups paid by consumers equals

$$\phi\nu \left(\sum_{k \in K^N} Y_k^N + \sum_{k \in K^R} Y_k^R \right) = \nu \sum_{k \in K^R} Y_k^R.$$

The latter equality holds by (11); that is, either $\nu = 0$ or the left hand side inequality in (11) holds with equality. The total income has to be divided over the total amount of certificates on the market, which is $\sum_{k \in K^R} \alpha_k Y_k^R$. Therefore, instead of ν , we are going to pay firms an adjusted certificate price $\tilde{\nu}$, which is determined as follows:

$$\tilde{\nu} = \frac{\nu \sum_{k \in K^R} Y_k^R}{\sum_{k \in K^R} \alpha_k Y_k^R}.$$

As mentioned above, due to the different interpretation of ν in (11), such an adjustment was not necessary in the UK banding system. In the investment model we incorporate the above condition as the following equality that will have to hold at the second stage:

$$\sum_{k \in K^R} (\tilde{\nu} \alpha_k - \nu) Y_k^R = 0. \tag{19}$$

The resulting pricing scheme then becomes

$$\begin{aligned}
p_{ik}^N &= p_i^N & \forall i \in I, k \in K^N \\
p_{ik}^R &= p_i^N + \alpha_k \tilde{\nu} & \forall i \in I, k \in K^R \\
p_i^C &= p_i^N + \phi \nu & \forall i \in I.
\end{aligned} \tag{20}$$

It can easily be seen with (11) and (19) that this new scheme is revenue adequate for the alternative banding system.

Although this alternative system guarantees that the original obligation target on production is satisfied, there are a few drawbacks to this system. First of all, the price of a certificate is no longer determined by the secondary trading market. The regulator has to intervene and buy certificates from firms at an adjusted price that is influenced by both the technology mixture and the mark-ups paid by consumers. The intervention in the trading process is likely to come with a certain administrative burden. Second, as we will see in more detail in our numerical study, the consumer price is much more sensitive to the technology mixture and in particular is higher when a large share of the production is done with a technology with a banding coefficient higher than 1. Furthermore, the consumer price could even increase as a result of a cost reduction (due to for example innovation) of a technology; this, we do not observe in the UK banding system. However, as we will show in our numerical study, in the UK banding system cost reductions can potentially lead to more polluting technology mixtures.

5 Introducing Uncertainty

The previously introduced models all assume a deterministic world. In reality however, demand can be uncertain due to seasonality and daily changes in, for example, weather patterns, and also the output of renewable power plants may vary from day to day, hour to hour. For example wind turbines are depending on daily weather conditions and influenced by the actual wind speed. A unit investment in wind energy does not mean we can produce a given amount of power at all times. We refer to this uncertainty as the uncertainty in availability of capacity.

The way we deal with uncertainty can be explained as follows. At the first stage, only the underlying probability distributions (which can be simply based on past empirical data) of the demand and availability of capacity are known; firms have to make decisions on their optimal investment quantities without knowing the outcome of the random variables. At the second stage the realizations are revealed to the firms. When firms make their first stage decision, they view the second stage as a short-run process that repeats itself over and over again. Each realization of the random variable can for example be seen as the realization associated with a particular day (or even an hour). On every day of the year there is an outcome, and the first stage decision is taken at the beginning of the year. Hence, the first

stage decision is a long-term decision. When making the decision, we take either the expectation or the sample average (in case we use a sampling technique) over all days and determine the investment level based on the expected or sample averaged second stage outcome.

When moving to the stochastic setting, a couple of modifications to the proposed models are needed. First, consider the basic two-stage model consisting of the first stage problem consisting of (1), (2), and (3) and the second stage problems (4), (5), (6), and (7). At the first stage, we assume the available renewable capacity at the second stage and the second stage demand to be unknown to the firms. At the second stage, ω will be a vector containing the uncertainties in available capacities and demand. Outcomes of the associated random variables are assumed to be revealed to firms at the second stage. To incorporate uncertain availability of capacity, for $k \in K^R$, $i \in I$ we define $F_{ik}(x, \omega)$ as some differentiable random function of the investment amount x of technology k in supply node i . For given ω we call $F_{ik}(x, \omega)$ the realized available capacity in technology $k \in K^R$ in node $i \in I$. Uncertain demand in demand node $n \in N$ is denoted by $d_n(\omega)$. At the first stage, given the probability distributions (or historical data) of the random variables at the second stage, long-term profits are maximized and the corresponding optimal investment quantities are determined. Long-term profits now consist of the expected second stage profits minus the first stage investment cost. For non-renewable generator $k \in K^N$ the first stage problem becomes:

$$\max_{x_k^N \geq 0} E_\omega \left[\sum_{i \in I} (p_{ik}^N(\omega) - c_{ik}^N) y_{ik}^N(x_k^N, \omega) \right] - \sum_{i \in I} \kappa_{ik}^N x_{ik}^N. \quad (21)$$

For renewable generator $k \in K^R$ the first stage problem becomes:

$$\begin{aligned} \max_{x_k^R \geq 0} \quad & E_\omega \left[\sum_{i \in I} (p_{ik}^R(\omega) - c_{ik}^R) y_{ik}^R(x_k^R, \omega) \right] - \sum_{i \in I} \kappa_{ik}^R x_{ik}^R \\ \text{s.t.} \quad & \sum_{i \in I} x_{ik}^R \leq M_k^R \quad (\zeta_k^R). \end{aligned} \quad (22)$$

The second stage for given x and ω is given by the OPF problem (14) with ω attached to all variables, d , and F , and without the fourth constraint that deals with the renewable obligation. The renewable obligation constraint is instead going to be imposed as a first stage constraint, as we explain below. For

given x and ω , we thus solve the following problem at the second stage:

$$\begin{aligned}
Z(x, \omega) := & \min_{y(\omega), \delta(\omega), f(\omega)} \sum_{i \in I} \sum_{k \in K^N} c_{ik}^N y_{ik}^N(\omega) + \sum_{i \in I} \sum_{k \in K^R} c_{ik}^R y_{ik}^R(\omega) + VOLL \sum_{j \in N \cup I} \delta_j(\omega) \\
s.t. & y_{ik}^N(\omega) \leq x_{ik}^N & (\beta_{ik}^N(\omega)) & \forall i \in I, k \in K^N \\
& y_{ik}^R(\omega) \leq F_{ik}(x_{ik}^R, \omega) & (\beta_{ik}^R(\omega)) & \forall i \in I, k \in K^R \\
& \sum_{k \in K^N} y_{jk}^N(\omega) + \sum_{k \in K^R} y_{jk}^R(\omega) + \delta_j(\omega) + f_j(\omega) \geq d_j(\omega) & (p_j^c(\omega)) & \forall j \in N \cup I \\
& \sum_{j \in N \cup I} f_j(\omega) = 0 & (\rho(\omega)) & \\
& \sum_{j \in N \cup I} PTDF_{l,j} f_j(\omega) \leq h_l & (\lambda_l^+(\omega)) & \forall l \in L \\
& \sum_{j \in N \cup I} PTDF_{l,j} f_j(\omega) \geq -h_l & (\lambda_l^-(\omega)) & \forall l \in L \\
& y_{ik}^N(\omega) \geq 0 & & \forall i \in I, k \in K^N \\
& y_{ik}^R(\omega) \geq 0 & & \forall i \in I, k \in K^R \\
& \delta_j(\omega) \geq 0 & & \forall j \in N \cup I.
\end{aligned} \tag{23}$$

The stochastic version of the basic model now consists of (21) for all $k \in K^N$ and (22) for all $k \in K^R$ at the first stage and (23) for all $\omega \in \Omega$ at the second stage.

When introducing a renewable obligation and a banding system, we need to make a few adjustments to the basic model. In all three systems, we replace the second stage obligation by its stochastic equivalent that is going to be imposed ex-ante, on the expected (or in numerical experiments sample-averaged) yearly production. This means that from day to day the obligation may be violated, but (in expectation) the end of the year target should be met. As such, we are interested in the ex-ante certificate price which depends on the underlying distribution (or historical data) of the random variable, but is fixed over the year. Notably, we replace (11), (17), and (19) with (24), (25), and (26), respectively; see below.

In principle, it is possible to consider a daily obligation as an alternative. The obligation should then be a second stage constraint (omitting the expectation) and each day (that is, in each realization) there could be a different certificate price. This implies that the certificate price will be fluctuating over the days. In this paper, we focus on having the obligation constraint over a certain period, since this is what is applied in reality (see for example Bertoldi and Huld (2006) and Van der Linden et al. (2005)).

In addition to replacing the obligation, we also need to adjust the pricing schemes (12), (18), and (20) in the original obligation system, the UK banding system, and the alternative banding system, respectively. We simply add ω s to the prices. With these modified pricing schemes, in

expectation the mark-ups paid by consumers cover the rewards. However, due to the uncertain outcome at the second stage, ex-post there may exist gaps between daily rewards to be paid and daily income from mark-ups. Focusing on such situations in more detail may be interesting for regulators aiming at daily revenue adequacy; however, it is outside the scope of this paper.

Finally, as a consequence of moving the obligation from the second to the first stage problem, in each of the systems the objective function of the OPF problem (23) needs a modification. All the necessary modifications to the obligation and the objective function of (23) are summarized below.

- **No banding:**

- Replace (11) at the second stage by the first stage condition

$$0 \leq E_\omega \left[\sum_{k \in K^R} (1 - \phi) Y_k^R(\omega) - \sum_{k \in K^N} \phi Y_k^N(\omega) \right] \quad \perp \quad \nu \geq 0. \quad (24)$$

- Replace the objective function of (23) by

$$\min_{y(\omega), \delta(\omega), f(\omega)} \sum_{i \in I} \sum_{k \in K^N} (c_{ik}^N + \phi \nu) y_{ik}^N(\omega) + \sum_{i \in I} \sum_{k \in K^R} (c_{ik}^R - (1 - \phi) \nu) y_{ik}^R(\omega) + VOLL \sum_{j \in N \cup I} \delta_j(\omega).$$

- **UK banding:**

- Replace (17) at the second stage by the first stage condition

$$0 \leq E_\omega \left[\sum_{k \in K^R} (\alpha_k - \phi^{UK}) Y_k^R(\omega) - \sum_{k \in K^N} \phi^{UK} Y_k^N(\omega) \right] \quad \perp \quad \nu \geq 0. \quad (25)$$

- Replace the objective function of (23) by

$$\min_{y(\omega), \delta(\omega), f(\omega)} \sum_{i \in I} \sum_{k \in K^N} (c_{ik}^N + \phi^{UK} \nu) y_{ik}^N(\omega) + \sum_{i \in I} \sum_{k \in K^R} (c_{ik}^R - (\alpha_k - \phi^{UK}) \nu) y_{ik}^R(\omega) + VOLL \sum_{j \in N \cup I} \delta_j(\omega).$$

- **Alternative banding:**

- Replace (11) at the second stage by the first stage condition (24).
- Replace (19) at the second stage by the first stage condition

$$E_\omega \left[\sum_{k \in K^R} (\tilde{\nu} \alpha_k - \nu) Y_k^R(\omega) \right] = 0. \quad (26)$$

- Replace the objective function of (23) by

$$\min_{y(\omega), \delta(\omega), f(\omega)} \sum_{i \in I} \sum_{k \in K^N} (c_{ik}^N + \phi \nu) y_{ik}^N(\omega) + \sum_{i \in I} \sum_{k \in K^R} (c_{ik}^R - \alpha_k \tilde{\nu} + \phi \nu) y_{ik}^R(\omega) + VOLL \sum_{j \in N \cup I} \delta_j(\omega).$$

To analyze these models, we carry out a numerical study in the next section, where we use sampling to deal with the uncertainty. We take M random samples from the given probability distributions. Then, each realization is denoted by ω_m , $m = 1, \dots, M$, and for each of these realizations the second stage problem is solved. At the first stage we then deal with the expectations by taking sample averages over all realizations.

6 Numerical Study

In this section we analyze the effects of the different renewable obligation systems on investments, prices, and CO₂ emissions in a numerical framework. In order to keep things tractable and solvable in a reasonable amount of time, we consider a small system. The setting is rigorously simplified in terms of network effects, but nonetheless we can draw some conclusions about possible side effects of the systems and make a comparison between them.

We are going to focus on three different renewable obligation policies:

- **No banding:** There is no banding mechanism, meaning all α_k s for renewable technologies are equal to 1.
- **UK banding:** The banding mechanism that is currently applied in the UK is imposed, under the assumption that Calculation A sets the target; the obligation is expressed as the number of certificates per MWh of power produced.
- **Alternative banding:** The banding mechanism as proposed in Section 4.2 is imposed; the obligation is expressed as the amount of power that should come from a renewable resource per MWh of power produced, and rewards are adjusted in order to guarantee long term revenue adequacy.

First, for different target levels we depict investments, prices, and CO₂ emissions in order to analyze the effects of the different systems and to get insight in their advantages and disadvantages. Second, it is reasonable to expect that after a technology is given support, more innovation and development will take place and subsequently that investment costs decrease. We therefore analyze the effects of a cost reduction of one of the technologies in the second part of this section.

We consider a single node and hence assume there is no limited network capacity on the transmission lines. For a thorough analysis of investment under uncertainty in transmission capacity in the UK electricity market, we refer to Van der Weijde and Hobbs (2012). We instead focus on the direct effects of obligation policies in absence of network limitations. We consider five

firms, each having a unique technology at their disposal. Non-renewable technologies coal and closed cycle gas turbine (CCGT) are used by firms 1 and 2, respectively. Renewable technologies onshore wind (ONW), offshore wind (OFFW), and landfill gas (LFG), are used by firms 3, 4, and 5, respectively. In addition there are two demand nodes, nodes 6 and 7. Table 1 contains the characteristics of the technologies, consisting of per unit production costs (c_k), investment costs (κ_k), tons of CO₂ emission per unit production (e_k), and the banding coefficient (α_k). The CO₂

Table 1: Characteristics of the technologies.

	Coal	CCGT	ONW	OFFW	LFG
c_k	22.1	50.2	0	0	21.1
κ_k	30.24	12.96	25.62	53.48	24.78
e_k	1	0.35	0	0	0.2
α_k	0	0	1	2	0.25

emission per unit production, e_k , is given to indicate how polluting the technologies are. The cost figures are in Pounds and based on data in MottMacDonald (2010). It is quite common in numerical studies to work with levelized cost of investment; that is, the investment cost that is needed to produce 1 MWh of electricity, taking into account that not every MW installed will be available at all times. We ignore this when defining the investment costs that play a role at the first stage, and will thus work with the real investment cost that is involved with having 1 MW of capacity installed. The fact that not all installed capacity is available for the full 8760 hours in the year is taken into account at the second stage via the function $F(\cdot)$ that we specify below.

Demand $d_n(\omega)$ in demand nodes $n = 6, 7$ are independent and are sampled from uniform distributions with lower bound a_n and upper bound b_n as in Table 2.

Table 2: Parameters for uniform demand distribution.

	a_n	b_n
6	8	12
7	15	20

The available wind and landfill gas capacities are also randomly distributed. As a function representing the realized available capacity of technology k we take $F_k(x, \omega) = \theta_k(\omega)x$, where for each renewable technology $\theta_k(\omega)$ is sampled from a uniform distribution with lower bound a_k and upper bound b_k , $k = 3, 4, 5$, as in Table 3. We assume onshore and offshore wind are fully correlated, but assume independence between wind and landfill gas realizations. We chose uniform distributions out of sheer convenience; one can choose alternatives which may fit the empirical data closely or even use empirical data itself.

Table 3: Parameters for uniform renewable output distribution.

	a_k	b_k
<i>ONW</i>	.2	.36
<i>OFFW</i>	.33	.45
<i>LFG</i>	.5	.774

Finally, as investment in landfills in the UK is limited by law, we impose a maximum investment in LFG of 5 units. We take a sample of size 3000.

6.1 Effects of Varying the Obligation Target

In this section we compare the three obligation systems in terms of investment quantities, prices, and CO₂ emissions for various obligation targets; that is, we let the obligation target range from 0 to 0.5 with increments of 0.01.

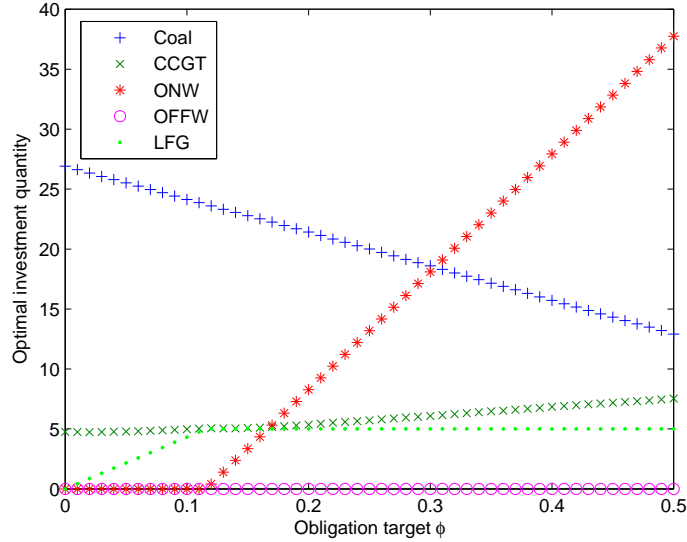


Figure 1: *Investment quantities in the no banding system.*

In Figures 1, 2, and 3 the effects of an increasing obligation target ϕ on investments are depicted. In Figure 1 the original obligation system without bandings is imposed. For low levels of ϕ we see that LFG is the only renewable technology in the mixture. As soon as it reaches its maximum capacity of 5 at $\phi = 0.12$, investments in ONW begin. There are no financial incentives to invest in OFFW (though in reality there may actually be investments in OFFW for other reasons than profit maximization, like geographic and regulatory constraints limiting onshore wind power). Investments in coal are decreasing with ϕ , but for the other conventional technology, CCGT, we observe a slight increase as ϕ increases. From our numerical output data we

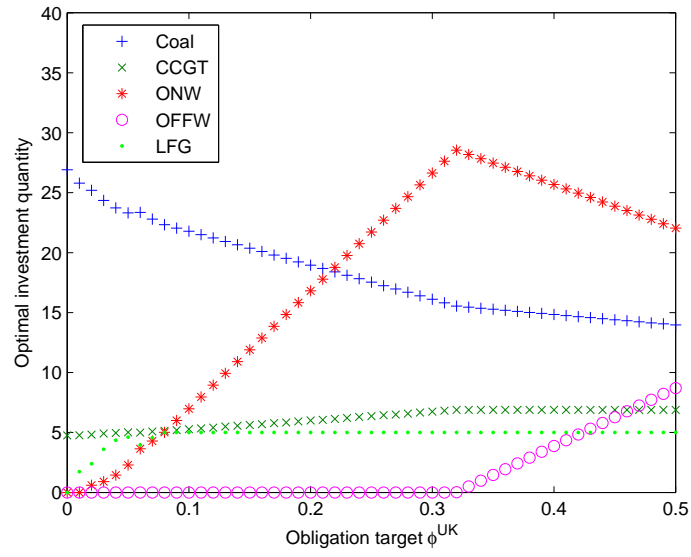


Figure 2: *Investment quantities in the UK banding system.*

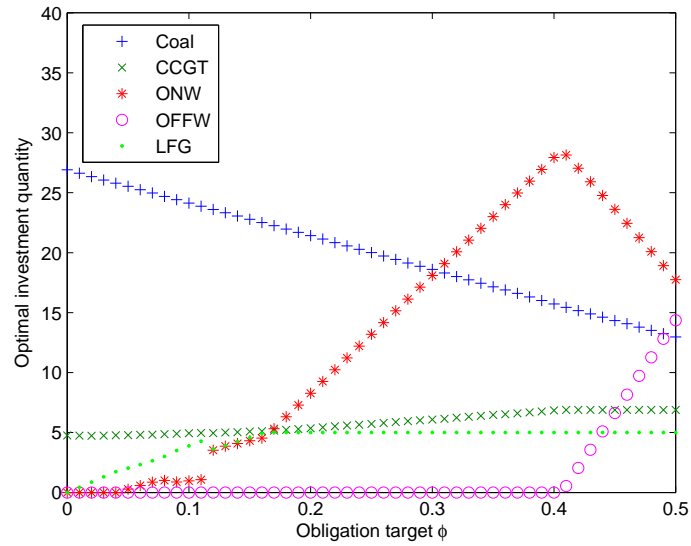


Figure 3: *Investment quantities in the alternative banding system.*

conclude that CCGT acts as a peak load technology, as it is mainly used for producing electricity in cases of high demand and/or low wind. More investment in ONW leads to more intermittency in the system. Consequently, to deal with the growing intermittency, more investment in the peak load technology, CCGT, will be done. Since investment in CCGT is cheaper than investment in coal, CCGT is preferred as a peak load technology. In the literature it is also often argued or even assumed that CCGT and gas in general are suitable technologies for dealing with intermittency due to its low capital cost and relatively fast start-up times (see for example DeCarolís and Keith (2006), Strbac (2002), Strbac et al. (2007)). Concluding, one can say that the obligation reduces CO₂ emissions in two ways: directly, via the replacement of coal by ONW, and indirectly, via the replacement of coal by the cleaner CCGT.

In Figure 2 investments under the UK banding system are depicted. We observe three major differences compared to Figure 1. First of all, for low levels of ϕ^{UK} , there are no investments in ONW in the original obligation system (Figure 1). However, in the UK banding system both LFG and ONW are in the mixture. This is caused by the fact that firms have to satisfy a target expressed in certificates and LFG is only rewarded with 0.25 certificates per unit production. Secondly, we observe positive investments in OFFW for high levels of ϕ^{UK} . Starting from $\phi^{UK} = 0.33$, we see a trade off between ONW and OFFW investments. From the fact that OFFW is not in the optimal mixture until $\phi^{UK} = 0.33$, we can conclude that for the UK banding system to be effective in encouraging investments in OFFW one needs rather high target levels. In general one can conclude that the UK banding system is certainly not effective in giving incentives to invest in OFFW for all target levels. A third observation is that, as OFFW investments increase, there is no need for additional CCGT investments like we observed in Figure 1. This is due to the fact that OFFW is more reliable than ONW. As a consequence, investments in coal decrease less rapidly when OFFW is in the mixture.

Investments under the alternative banding system are depicted in Figure 3. For lower levels of ϕ we observe less investments in renewables than in the UK banding system, but about as much as in the original obligation system. A more obvious observation is that investment in OFFW begins at $\phi = 0.41$, which is much later than in the UK banding system (Figure 2). Hence, the alternative system needs higher obligation targets in order to succeed in giving financial incentives to invest in OFFW. The reason for this difference is the contribution of OFFW to satisfying the obligation target. In the UK system a unit production with OFFW is rewarded with 2 certificates and hence contributes to the target on certificates twice as much as ONW. In the alternative system a unit production with OFFW only contributes one unit to satisfying

the target on renewable production. Hence, OFFW only enters the mixture when it has a cost advantage over ONW due to the higher bandings. In addition it appears that once OFFW has this cost advantage and is in the mixture, investments will increase more rapidly with ϕ compared to the UK banding system in which OFFW is mainly in the mixture to satisfy the target on certificates.

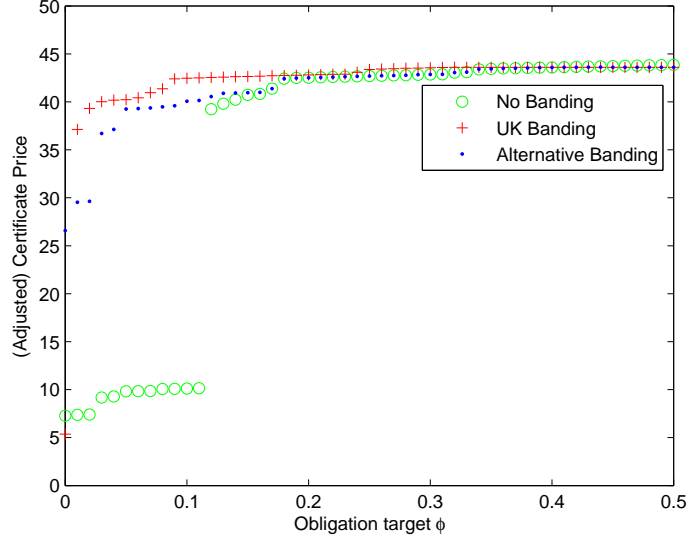


Figure 4: *The certificate price ν in the no banding and UK banding systems, and the adjusted certificate price $\tilde{\nu}$ in the alternative banding system.*

In Figure 4 the certificate prices are shown. For the original obligation system and the UK banding system we use the certificate price ν , while for the alternative banding system we use the adjusted certificate price $\tilde{\nu}$. Hence, what we observe in the figure is the rewards firms get per certificate. In general the certificate price is set in such a way as to make renewable technologies competitive compared to nonrenewable technologies (and eventually other renewables). We observe that without bandings and for ϕ up to 0.11, the certificate price can be low since LFG is relatively cheap. For higher ϕ and in the banding systems, ONW and OFFW are needed to satisfy the target and hence ν has to increase in order to make those technologies competitive. Since the production and investment costs in all three systems are the same, the reward needed for making a technology competitive is almost the same. Furthermore, it can be seen that the curves are relatively insensitive to changes in ϕ for $\phi > 0.11$. This can be explained by the fact that once the adequate level of ν is reached, there is no need for a higher reward.

Figure 5 shows the average consumer prices. Since we have different prices in each realization we look at the average price, \bar{p}^c , over all realizations. As consumers pay $p^c = p^N + \phi\nu$ with ν

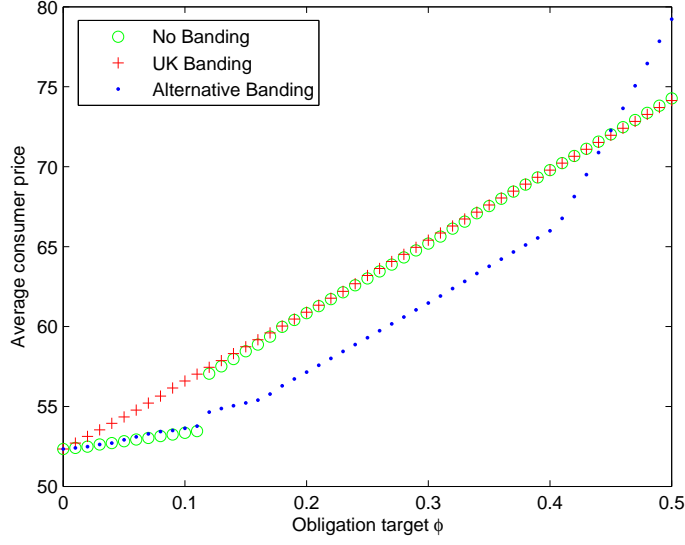


Figure 5: *The average consumer price.*

relatively constant with respect to ϕ , as we saw in Figure 4, it is not surprising that in all three systems the average consumer price is increasing with ϕ . In the no banding system, the average price makes a jump when ϕ moves from 0.11 to 0.12, which is caused by the fact that ONW came into the mixture. In the UK banding system, there is no such jump, since ONW is in the optimal mixture also for low values of ϕ . From the figure we may conclude that going from the original obligation system to the UK banding system does not necessarily increase prices. Other than in the lower regions, the average prices in the no banding and UK banding systems are almost equal, meaning that the additional financial incentive given to OFFW in the form of a relatively high banding does not affect consumer prices. In the alternative banding system prices are in general lower than or equal to the prices in the other two systems, except for very high levels of ϕ ($\phi \geq 0.45$). Hence, in the alternative system the financial incentive given to OFFW does result in higher (average) consumer prices. This is caused by the fact that the reward per certificate will remain the same as we observed in Figure 4, while the total number of certificates significantly increases due to the larger amount of OFFW in the mixture. This is reflected in the consumer prices.

The realized renewable production as fractions of total production in the three scenarios are depicted in Figure 6. By the way the obligation was imposed in both the no banding and the alternative banding system the fraction will automatically be equal to ϕ , meaning that the target is actually satisfied. In the UK banding system, as long as only LFG and ONW are in the mixture, we are overshooting the target. However, for high levels of ϕ the original target on

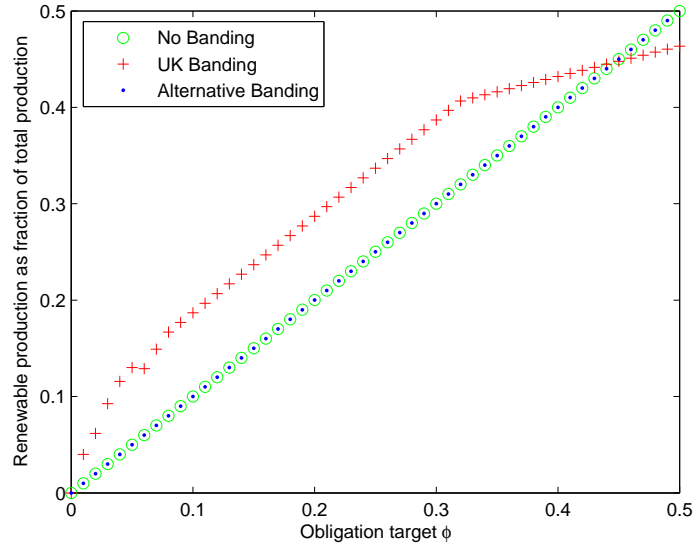


Figure 6: *The renewable production as a fraction of total production.*

renewable production would be violated due to the increased amount of OFFW production. As a unit production with OFFW contributes two units to satisfying the target on certificates, less total renewable production is needed to satisfy this target.

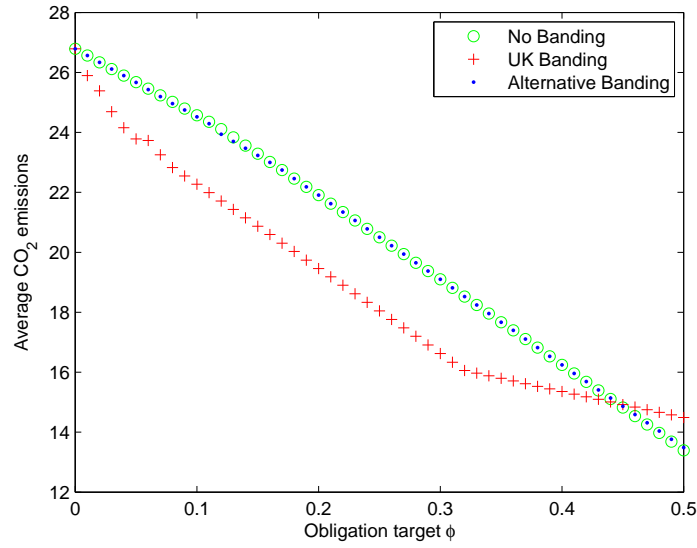


Figure 7: *The average CO₂ emissions.*

In Figure 7 the average CO₂ emissions over all realizations are depicted. We see that, as one would expect, CO₂ emissions are decreasing with ϕ . Under the UK banding policy, for low and medium levels of ϕ there is less emission than in the other systems, because of the higher fraction of renewable production (as observed in Figure 6). This is mainly the case when OFFW is not

in the optimal mixture. However, for higher levels of ϕ , when a significant amount of OFFW is in the mixture, we observe that the UK banding system leads to higher levels of CO₂ emission compared to the other systems.

To summarize, a renewable obligation leads to more financial incentives for investments in renewable resources. When OFFW is given more support in the form of a higher banding, for relatively high obligation levels this support becomes effective. However, this may come at the cost of more CO₂ emissions in the UK banding system and significantly higher consumer prices in the alternative banding system.

6.2 Sensitivity to Decreasing Investment Costs

One goal of a banding system is to encourage development in less established technologies like offshore wind power. As technologies get more established, investment costs are likely to go down in the long run (learning by doing). We now assume that due to the extra support for offshore wind that is given by the banding systems, the investment cost of OFFW is going to decrease. In this section we will therefore analyze the effect of a small decrease in the unit investment cost of OFFW of 0.42 to $\kappa_4 = 53.06$. Assuming that operating and management costs remain the same, this means a decrease of 32.5 per KW of installed capacity (which is approximately 1% of the original building cost per KW).

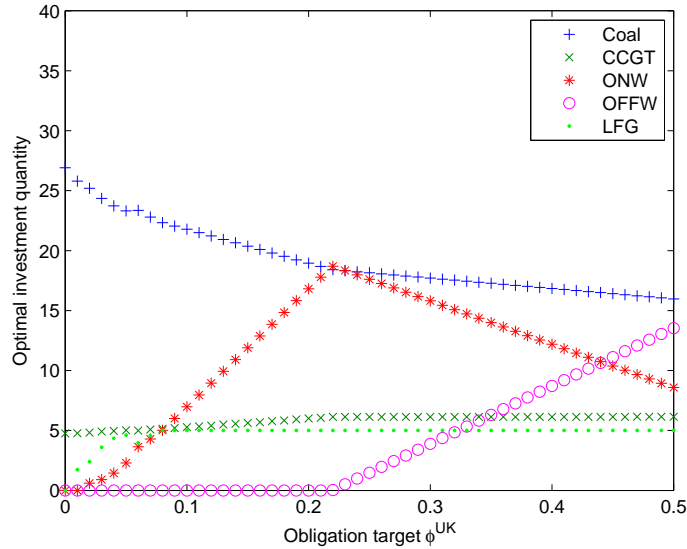


Figure 8: *Investment quantities in the UK banding system.*

In Figures 8 and 9 the investment quantities in the UK and alternative banding systems, respectively, are shown. Investment decisions in the original obligation system will be the same

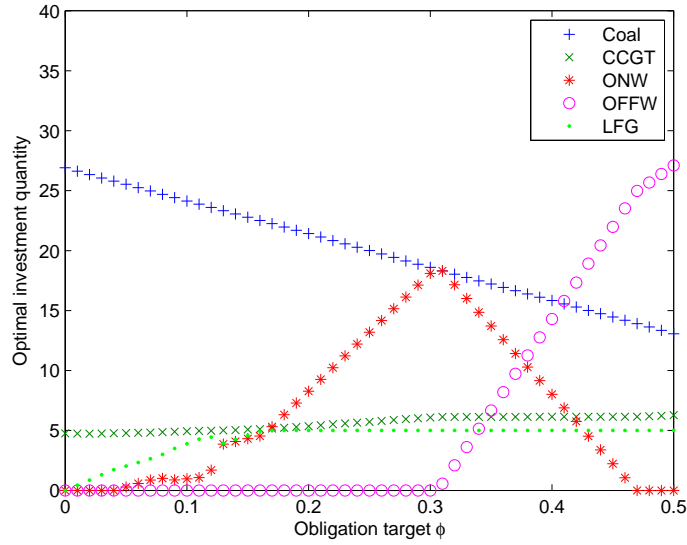


Figure 9: *Investment quantities in the alternative banding system.*

as in Figure 1. Comparing Figure 2 to Figure 8, it is obvious that a small decrease in the OFFW investment cost can have quite an impact on investment strategies. In Figure 2 a target of 0.33 is needed for OFFW to come into the mixture, whereas with the lower investment cost a ϕ of 0.22 is sufficient. The same comparison can be done for Figures 3 and 9. In Figure 3 a ϕ of 0.41 is needed to induce investments in OFFW, whereas in Figure 9 a ϕ of 0.31 is sufficient. Afterwards, investments in OFFW are increasing rapidly with ϕ , and ONW investments even go to zero. Comparing Figure 8 to Figure 9 we observe that again the UK banding system needs lower targets in order to induce investments in OFFW, but that for high levels of ϕ investments in OFFW are not increasing as rapidly as is the case in the alternative system.

Figure 10 shows the average consumer prices after the cost reduction in OFFW. In the no banding and UK banding systems we observe nearly the same average prices as those observed in Figure 5. In the no banding system this is not surprising as OFFW is not in the mixture. In the UK banding system for high levels of ϕ there is more OFFW in the mixture than before the cost reduction. This additional OFFW does not influence the average consumer price. The consumer price consists of p^N , the price nonrenewable generators receive, which is independent of OFFW investment cost, plus $\phi\nu$, the mark-up. As ν is not influenced by the amount of OFFW in the mixture, the consumer price is not affected by a different mixture either. Obviously, in the alternative banding system OFFW does affect the average consumer price. Although the reward per certificate remains the same, the number of certificates significantly increases with the amount of OFFW investments. To cover the expenses of the increased number of certificates,

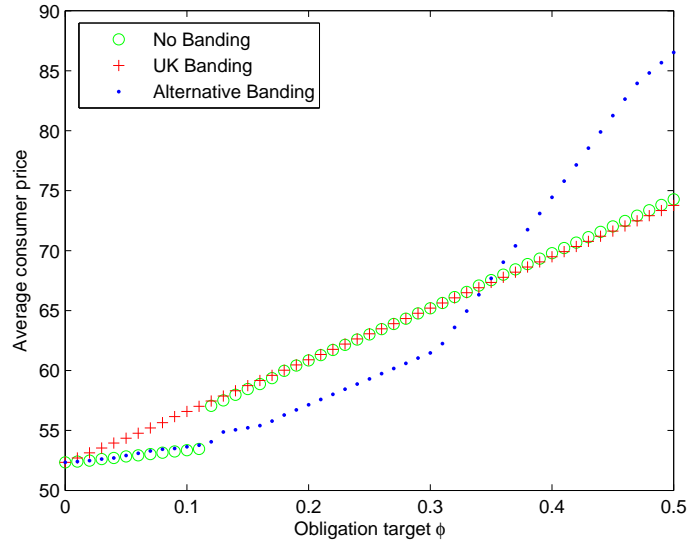


Figure 10: *The average consumer price.*

consumer prices increase. We may conclude that in the alternative banding system consumers pay for the additional financial support that is given to OFFW. A reduction in OFFW investment cost can thus lead to a higher average consumer price.

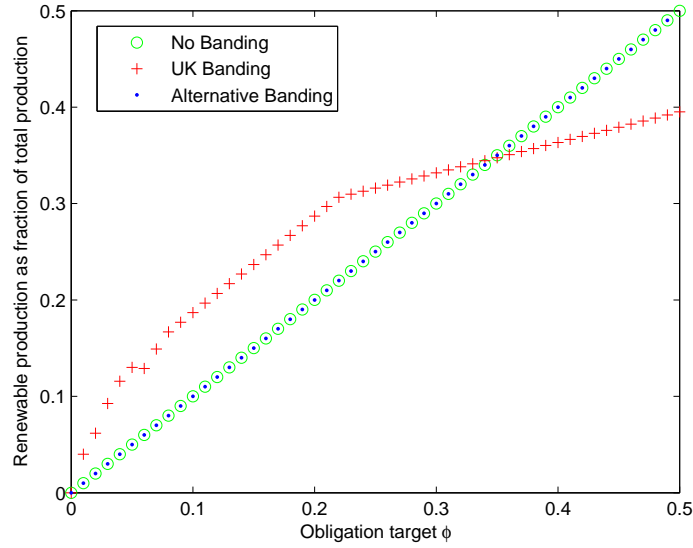


Figure 11: *The renewable production as a fraction of total production.*

Figures 11 and 12 contain the fraction of renewable production and the expected CO_2 emissions, respectively. It can be seen that in the no banding and alternative banding system the obligation target is satisfied, and that CO_2 emissions are nearly the same. This was also observed in Figures 6 and 7. Hence, while prices are relatively stable in the UK banding system, emissions

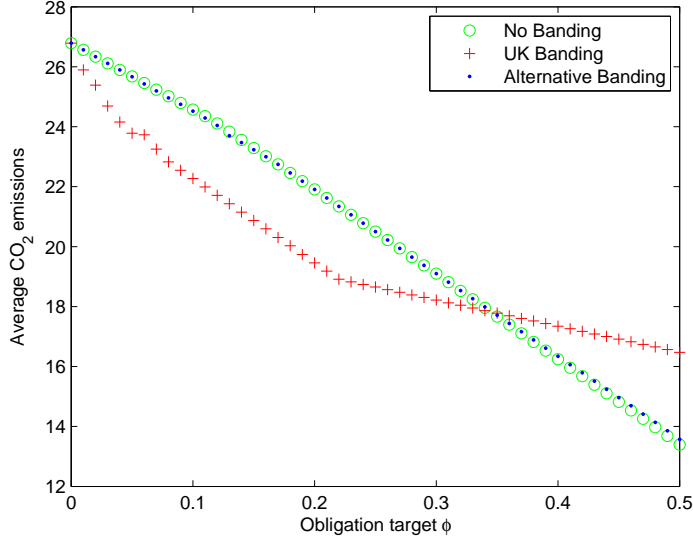


Figure 12: *The average CO₂ emissions.*

are relatively stable in the original obligation and alternative banding system. In the UK banding system, the fraction of renewable production and the expected CO₂ emissions are affected by the cost reduction. As can be seen from Figure 11, for $\phi \geq 0.35$ the obligation target is not satisfied, while it was satisfied up to $\phi = 0.44$ before the cost reduction. Also, when comparing Figures 7 and 12 we see that the cost reduction leads to more emissions for $\phi \geq 0.22$. The different mixture as a result of the OFFW cost reduction thus results in a more polluting system. Obviously this is a negative side effect of having the target on certificates, while OFFW receives 2 certificates per unit production when only producing a single unit of renewable electricity. Calculation B could potentially improve the situation as it would put a higher target on certificates, but one should at least be cautious about the possible side effects of an obligation on certificates.

To summarize, when a technology with a high banding manages to reduce its cost, banding mechanisms may cause unwanted side effects. In the UK banding system a cost reduction in OFFW may lead to increased levels of CO₂ emission, whereas in the alternative system it may lead to increased consumer prices. A possible solution when OFFW costs are reduced, is reducing its banding coefficient accordingly.

7 Conclusions

This paper modeled and analyzed three different renewable obligation policies in a mathematical framework. The original (UK) renewable obligation, the renewable obligation including the UK

banding system, and a proposal for an alternative banding system have been modeled in the electricity market investment model that was originally introduced by Gürkan et al. (2012). Then a numerical study shed some light on the possible advantages and disadvantages of each system and we have observed a couple of side effects.

The main goal of the renewable obligation is to reduce CO₂ emissions by reducing investments in polluting technologies and to have them replaced by renewable ones. As we observed in our numerical study, CO₂ emissions are curbed both directly by the replacement of coal by onshore wind, and indirectly by the replacement of coal by the cleaner CCGT. While we see an increasing investment in onshore wind and to a lesser extent landfill gas, a major concern is that in the long term targets may not be met without investment in less developed technologies like offshore wind. As can also be observed in our numerical study, the renewable obligation fails to give the right financial incentives to these less developed technologies. This is the main reason why a banding system was introduced in the UK in 2009. Rather than rewarding each unit production with a renewable resource with the same amount of certificates, more certificates and hence more support is given to the technologies that needed additional incentives.

We find that the banding system can be successful in giving incentives to OFFW, but that rather high targets are needed in order to do so. Once there is a substantial amount of investment in OFFW, we observe that the original obligation target on production may not be met. This is caused by the fact that a unit production with OFFW adds two units to satisfying the obligation target whereas it only adds one unit of renewable energy. This problem may be magnified when less developed technologies like tidal and wave power enter the optimal mixture. They need more support as stressed out by Allan et al. (2011), and therefore they have banding coefficients of 3 and 5, respectively.

We then proposed an alternative banding system, which guarantees that the original obligation target on production is always satisfied. On the downside, based on our numerical study it is expected that in the alternative system prices will significantly rise and that even higher targets are needed in order to give incentives for investment in tidal and wave power.

It is expected that more support for OFFW is going to cause more development in OFFW and hence will result in a downward shift in OFFW investment cost in the long run. We analyzed the consequences of such a cost decrease and found that investment levels in different technologies are in general very sensitive. Since more OFFW comes into the optimal technology mixture, less investment in renewable technologies is needed to satisfy the obligation in the UK banding system. Therefore we find that a cost decrease in OFFW actually results in more CO₂ emissions.

We do not observe this in the alternative banding system, but there the prices are very sensitive to changes in cost and we find a significant increase in the consumer price. Obviously, bandings, besides its positive effects on less established technologies, can have certain negative side effects and can give the wrong message in the long run. When technologies succeed in reducing its cost as a result of the given support (learn by doing), the financial support should be reduced accordingly.

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